

CONCEPTS AND BENEFITS OF LUNAR CORE DRILLING. K. M. McNamara,¹ D.D. Bogard,¹ B.J. Derkowsky¹, J.A. George¹, R.S. Askew,¹ and J. F. Lindsay², ¹NASA Johnson Space Center, Houston, TX 77058 (karen.m.mcnamara@nasa.gov). ²Lunar and Planetary Institute, Houston, Texas 77058.

Introduction: Understanding lunar material at depth is critical to nearly every aspect of NASA's Vision and Strategic Plan[1]. As we consider sending human's back to the Moon for brief and extended periods, we will need to utilize lunar materials in construction, for resource extraction, and for radiation shielding and protection. In each case, we will be working with materials at some depth beneath the surface. Understanding the properties of that material is critical, thus the need for Lunar core drilling capability. Of course, the science benefit from returning core samples and operating down-hole autonomous experiments is a key element of Lunar missions as defined by NASA's *Exploration Systems Architecture Study*[2]. Lunar missions will be targeted to answer specific questions concerning lunar science and resources.

Science Potential: Several subsurface samples of the lunar regolith were taken by Apollo and Luna missions and returned to Earth. These samples were acquired by coring tubes manually driven into the surface to depths of less than one meter, and for later Apollo missions, by cores power-drilled to depths of 2-3 meters. These subsurface core samples proved to be of significant scientific value for understanding the nature and history of the lunar regolith. The regolith is a dynamic, evolving entity driven by meteoroid impacts at all scales. Large impacts excavate fresh bedrock to the surface and produce large-scale stirring, both laterally and vertically. Impacts also act to produce some melting, destruction of existing regolith "grains", and construction of new particles (agglutinates) from smaller particles.

Most regolith materials at a given site are produced from the local bedrock. However, because large impacts eject material to greater distances, some fragments at a given site represent different rock types located some distance away. For example, bright rays from the large craters Tycho and Copernicus extend outward for hundreds of kilometers. A ray from Copernicus crosses the Apollo 12 landing site, and Apollo 12 regolith contains a variety of material, which is not locally derived, which is rich in certain trace elements, and which is thought to be Copernicus ejecta. Radiometric dating of these Apollo 12 fragments have given the likely formation time of Copernicus at ~800 million years. As another example, the regolith returned by Apollo 11 was primarily basalt, but contained small fragments of Ca-rich plagioclase obviously foreign to the site. From this information, the prediction was made that this material represented typical lunar highlands, possibly formed by an early lunar magma ocean, a prediction confirmed by later missions.

The regolith surface captures the impinging solar wind and energetic solar particles, and regolith stirring by impacts cycles older solar products to deeper depths. Larger impacts produce some distinct layering of the regolith, and the times these layers were emplaced can be discerned from studies of products of high energy nuclear reactions from galactic cosmic rays. Studies of Apollo cores have identified deeper layers emplaced as much as a billion years ago. Lunar regolith having different times of surface exposure enables study of the history of solar particle emissions, but the record of the early sun has been significantly altered by regolith processes through time. Particularly valuable material for

study of early solar emissions would be regolith formed on a new basalt flow in the distant past, which was later covered by a new, thin flow and preserved. Such "fossil" regoliths are expected to be accessible on relatively young basalt flows, where the overlying regolith has only developed to depths of a few meters, and in the walls of craters, where different basalt flows are exposed. The time of generation of such a fossil regolith could be determined by radiometric dating of the confining basalt flows.

Determining the character of the lunar regolith at a given site will be essential for studies of in situ resource utilization, for engineering characteristics relevant to complex human operations, and for potential hazards to astronauts and equipment. To fully characterize the regolith at a given site requires knowledge of its diversity both in area extent and with depth. One or more deep core samples would be the most efficient way to sample variations in the regolith with depth. Core samples would be characterized as to their chemical composition, grain size distribution, soil maturity, solar wind content (especially hydrogen), and diversity of rock types. In addition, determining the detailed composition and chronology of uncommon rock fragments in the core may give important information about distant rock units not otherwise available.

Drill holes resulting from core extraction also have important scientific value. One use of the drill hole would be to measure the lunar heat flow at each site visited. Heat flow measurements taken at Apollos 15 and 17 indicated that the lunar heat flow is $\sim 2.8\text{-}3.1 \times 10^{-6}$ W/cm², or about half that of the Earth[3]. This is consistent with other data that indicate the Moon contains a lower concentration of radiogenic elements. However, a variety of data sets now indicate that heat producing nuclides such as U, Th, and ⁴⁰K are strongly concentrated in a large area of the lunar front-side called the Procellarum KREEP Terrain (PKT). Both of the Apollo heat flow measurements were conducted within or on the edge of the PKT, and consequently the heat flow from other parts of the Moon, especially the back-side, may be considerably less. Knowing both the global average heat flow and its regional variation is important to understanding the differentiation history of the Moon and its internal reology. A relatively deep hole in the regolith is required to make heat flow measurements, in part so as to be below the thermal cycles in the upper regolith produced by the diurnal rotation of the Moon.

Other types of subsurface analytical instruments could also be emplaced using the lunar drill. For example, a down-hole slim-line instrument could be used to measure natural background gamma radiation and determine the composition of the soil. Such instruments have been developed and used routinely by the petroleum industry.

In addition, the minimum depth of 5 meters provides the potential to hit bedrock in some areas of the younger lunar mare. This would be a scientifically unique sample, unlike any we have returned before. Results of scientific examination would impact our understanding of the moon's evolution as well as its composition and potential of the material for use as a resource. In addition, it would provide valuable engineering data for the design of future lunar outposts and

serve as a means for the “scouting of future lunar outpost locations”.

Technology: Apollo Lunar Surface Drill (ALSD). NASA has, of course, drilled on the surface of the moon before. The ALSD was developed as an integral part of the Apollo Lunar Surface Experiments Package (ALSEP). The ALSD, when stowed for launch, occupied a volume of approximately 54 X 28 X 12 cm and weighed 14 kg. The power head, or drill proper, weighed 4 Kg and drew 430 watts of power. It was a rotary percussion drill that delivered 2270 blows per minute and rotated at 280 rpm at the drill stem. The electric motor, prior to reduction, operated nominally at 9300 rpm. The drive passed through reduction gears and a clutch, which reduced the torque to a level that could be safely controlled by the astronaut. The battery was a silver oxide-zinc unit consisting of 16 cells that delivered 24v. The drill was designed to drill to a depth of 3.0 m. On Apollos 13, 15 and 16 six drill stems were carried, potentially allowing drilling to a depth of 2.5 m. On Apollo 17 all eight stems and a bit allowed drilling to 3.0 m. The drill stem section were made of titanium steel with an outer diameter of 25 mm and an inner diameter of 21 mm with four lead flutes cut to a depth of 0.8 mm to remove cutting from the drill hole[4]. The 6 cm long open-ended bit held five tungsten carbide cutting tips. The drill string lacked a core retainer in the bit and did not have a liner or split string mechanism for accessing the core. Upon return the core stems were opened in the Lunar Receiving Laboratory using a purpose-built milling machine to split the titanium steel string lengthwise allowing the top half of the sample to be removed.



Figure 1. Dave Scott deploying ALSD on Earth.

JSC/Baker Hughes Planetary Drilling System. This collaboratively developed drilling system provides coring drill technology that has the potential to penetrate many (>5) meters into the lunar subsurface.

The drill is comprised of three assemblies: a bottom hole assembly that provides the actual drilling function, a surface support assembly which provides the bottom hole assembly a method to traverse in and out of the hole and also assists in cuttings/core removal, and a drill control/power assembly that provides the avionics, control algorithms, and power supply to control the drill. The drill produces a continuous segmented core and cuttings from the hole of several meters or more. Individual core segments are approximately 15 cm in length and 2.5 cm in diameter. The system is based around an electrically-powered coring head suspended from a cable (powered wireline). Core segments, as well as cuttings, are brought to the surface for analysis. The drill is operated without a pipe string and without drilling fluid.

In the current design, that has been fabricated and field-tested, the bottom hole assembly is initially set in a short segment of pipe above the surface. A mechanical sidewall

anchor is set and fixes the upper portion of the bottom hole assembly in the rotational and axial axes. Once the anchor is fixed, a lead screw actuator is used to extend the lower portion of the bottom hole assembly to provide direct down force on the drill bit. In conjunction with the lead screw, a variable-speed, brushless DC motor turns a hollow drive shaft within a stationary outer tube in the lower portion of the bottom hole assembly. This drive shaft is a combination coring head and cuttings auger. The core head bit has been designed by Baker Hughes to allow a robust cutting surface optimized for multiple strata that may be encountered. As the drill progresses through the formation, a core is collected in the lower portion of the hollow shaft. At the same time, drill cuttings are carried up the annulus between the shaft and the outer tube, into a cuttings cup mounted in the upper portion of the hollow shaft. Drilling proceeds until the end of travel in the force-on-bit extension. (See Figure 2)

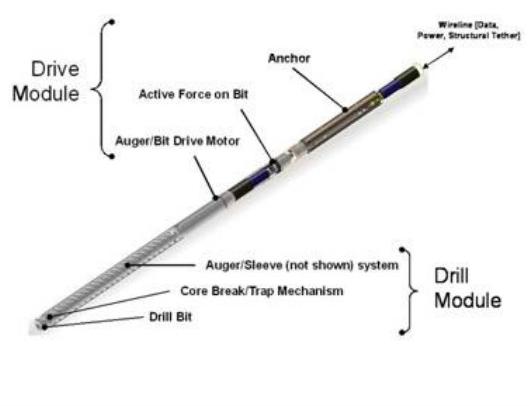


Figure 2. JSC/Baker Hughes Planetary Drilling System

At the end of drill cycle, the bottom hole assembly is retrieved to surface, the core and cuttings are removed, and the assembly is ready to be deployed into the hole for another drilling cycle. Servicing the drill, after initial deployment, requires assembly and disassembly of the lower barrel to remove cores and cuttings.

Technology readiness levels of between 5 and 6 describe the current state of hardware development. A version of the low mass prototype drill has been designed and built at the JSC with support from Baker Hughes. This drill has flight-like geometry and has been built to demonstrate key functionality, while adhering to flight-like mass limitations (the bottom hole assembly weights approximately 10 kg). The drill system has recently concluded a three year development and field test/demonstration campaign. During the culminating field test in the spring of 2006, 2 meters of native sandstone were drilled in the high arctic environment. Other formations drilled include ice, ice cemented sands, various types of basalt, sandstones, and free flowing sands.

Summary: The development of a lunar core drilling device which can operate to depths greater than 5 meters will greatly enhance the science obtain on future Lunar missions and is absolutely critical to meeting the goals of the Lunar Exploration Architecture. By combining the successful implementation of drilling achieved on the Apollo missions with the innovative technology of the JSC/Baker Hughes planetary drilling system, these goals can be achieved within the Architecture as it evolves and develops.

References: [1]NASA Strategic Plan (NASA 2006).
[2]NASA's *Exploration Systems Architecture Study* (NASA, 2005). [3]M. G. Langseth, et al. (1973) NASA SP330, 9-1.
[4] Martin Marietta Corporation (1969) MCR-69-300.